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Literature Review of Electric Barriers for Returning Adult Salmonids

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Connie D. Svoboda
Jarod Hutcherson

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Connie D. Svoboda, Bureau of Reclamation, Technical Service Center, Hydraulic Investigations and Laboratory Services, 303-445-2152, csvoboda@usbr.gov

Jarod Hutcherson, Bureau of Reclamation, Technical Service Center, Fisheries and Wildlife Resources, 303-445-2011, jhutcherson@usbr.gov

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Manmade diversions provide an unnatural route between river systems that may cause adult salmon to move away from natal spawning grounds. An electric barrier may be one possible alternative to redirect upstream migrating adult salmon back to their natal stream. This literature review identifies studies related to the effectiveness of upstream barriers at deterring migrating salmon and the effects of electricity on adult salmonid health, stamina, and reproductive capability. Studies pertaining to the effects of electricity on delta smelt (*Hypomesus transpacificus*) and sturgeon (in particular, green sturgeon, *Acipenser medirostris*) are included, since these federally-protected species may be present in locations where electric barriers are installed to guide adult salmon. The physical and electrical characteristics of an effective electrical array are discussed. The feasibility of developing an effective electrical barrier to divert upstream migrating adult Chinook salmon (*Oncorhynchus tshawytscha*) in the Mokulemne River that might otherwise pass through the Delta Cross Channel into the Sacramento River is evaluated.

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Executive Summary

Manmade diversions provide an unnatural route between river systems that may cause adult salmon to move away from natal spawning grounds. In these instances, poor hatchery return numbers or undesirable genetic mixing may occur. An electric barrier may be one possible alternative for redirecting upstream migrating adult salmon back to their natal stream. This literature review identifies studies related to the effectiveness of upstream barriers at deterring migrating salmon and the effects of electricity on adult salmonid health, stamina, and reproductive capability. Studies pertaining to the effects of electricity on delta smelt (*Hypomesus transpacificus*) and sturgeon (in particular, green sturgeon, *Acipenser medirostris*) are included, since these federally protected species may be present in locations where electric barriers are installed to guide adult salmon. A state-of-the-art on electric fish barriers is presented along with the physical and electrical characteristics of an effective electrical array.

An electrical barrier has been proposed by the Golden Gate Salmon Association in California to prevent upstream migrating adult Chinook salmon (*Oncorhynchus tshawytscha*) in the Mokelumne River from moving into the Sacramento River when Delta Cross Channel gates are open in the fall. Based on this literature review, a pulsed DC graduated field fish barrier may be effective for this application and the concept should be further investigated.

Introduction

Manmade diversions provide an unnatural route between river systems that may cause adult salmon to move away from natal spawning grounds. In these instances, poor hatchery return numbers or undesirable genetic mixing may occur (Quinn 1997). Electric barriers are one possible alternative to redirect adult salmon back to their natal stream. Electrical barriers have been successfully used to divert fish (Burrows 1957; Palmisano and Burger 1988) or prevent further movement into waterways (Swink 1999; Savino *et al.* 2001; Sparks *et al.* 2010).

Electric barriers are installed for many different types of fish including invasive species and native species (Pugh *et al.* 1970; Clarkson 2004; Sparks *et al.* 2010). Some electric barriers provide upstream guidance or deterrence in rivers or at fish hatcheries (Burrows 1957; McLain 1957). Some barriers provide downstream guidance in rivers or are used to exclude fish from power intakes (Pugh *et al.* 1970; Barwick and Miller 1990).

The goal of this scoping level study is to perform a targeted literature review that relates to the use of electric barriers to redirect upstream returning adult salmonids. Several questions were posed:

- Have electrical barriers have been installed for this purpose?
- How were the barriers designed?
- Were the barriers effective? If not, what were the problems?
- Does electricity affect adult salmonid health, stamina, or reproductive capability?

The literature review includes technical documents, reports, and research studies on the effectiveness of upstream barriers at deterring migrating salmon. Related studies using electrical barriers for other fish species or other purposes were included in the literature review if they were considered applicable. The literature review also includes studies pertaining to the effects of electricity on delta smelt (*Hypomesus transpacificus*) and sturgeon (in particular, green sturgeon, *Acipenser medirostris*), since these federally protected species may be present in locations where electric barriers are installed to guide adult salmon. Central Valley steelhead (*Oncorhynchus mykiss*) may also be present in the installation locations. Because of the similarities between steelhead and Chinook salmon (*Oncorhynchus tshawytscha*), much of the reviewed literature on Chinook salmon is pertinent to steelhead as well. This document also contains a description of state-of-the-art on electric barriers, including graduated electric barriers.

Purpose

An electric barrier has been proposed by the Golden Gate Salmon Association in California to prevent upstream migrating adult Chinook salmon in the Mokelumne River from moving into the Sacramento River when Delta Cross Channel gates are open in the fall. The Bureau of Reclamation (Reclamation) opens the gates from June 16 through October 31to improve the water quality of water exports to the South Delta according to State Water Resources Control Board Water Right Decision 1641 (State Water Resources Control Board 1999). In order to meet both objectives of preventing adult salmon from moving between water systems and keeping gates open to improve water quality, an electric barrier has been proposed on Dead Horse Cut or Snodgrass Slough (Figure 1).

Because each field location is unique (*e.g.*, waterway dimensions, bathymetry, target and non-target species present, complicating issues), this literature review first focuses on the physical and electrical characteristics of an effective electrical array. Second, the target species (in this case, adult Chinook salmon) is considered. This includes both the elements of an electric barrier that are important when deterring fish of this species/size as well as potential adverse effects (short- and long-term health, survival, and fecundity). Lastly, because threatened and endangered species may encounter the electric barrier, detrimental effects to these fish must also be considered. Once all of these elements are considered, the feasibility of developing an effective electric barrier with the intended purpose, diverting upstream migrating adult Chinook salmon that might otherwise pass through the Delta Cross Channel, is evaluated. Key points from reviewed literature are provided in Appendix A, Table 1.

Figure 1. Map of the Delta Cross Channel and surrounding area. An electric barrier is proposed on Dead Horse Cut or Snodgrass Slough to prevent movement of upstream migrating Chinook salmon from the Mokelumne River into the Sacramento River through the Delta Cross Channel.

State-of-the-Art on Electric Fish Barriers

Design of Electric Barriers

Electric fish barrier design typically involves submerging two or more metal electrodes in a fixed location and applying a voltage between them. Electrical current passes between the electrodes, forming an electrical field in the water. Fish within the field become part of the electrical circuit. The amount of current that passes through the fish depends on the relative conductivities between the fish and the water. The more similar the conductivity, the more efficiently power is transferred to the fish (Kolz and Reynolds 2000). Fish in contact with the electrical field can experience a reaction such as avoidance, electrotaxis (forced swimming), electrotetanus (muscle contraction), electronarcosis (muscle relaxation or stunning), or death (USGS 2001).

Large fish are generally more susceptible to electrical fields than smaller fish because more power is transferred for a given voltage gradient (volts per unit distance) over the length of the fish (Reynolds 1996). However, effects of the field on an individual depend on the specific location of the fish in the field and may also depend on the fish species. Maintaining field intensity low enough to avoid tetanus in larger fish should allow smaller fish to pass through the field unharmed.

Electric fish barriers are commercially available and have been used in a variety of situations including the restriction of fish movement during upstream passage. Electrical barriers can use alternating current (AC), direct current (DC), or pulsed DC. Alternating current was used in early fish barriers, but has since been found to be injurious to fish because alternating polarity causes electrotetanus. Direct current or pulsed DC is typically used in recent fish barrier applications. When pulsed DC is used, peak voltage, peak current, pulse width, and frequency are adjusted to elicit the desired fish response. Electrodes can be installed as vertical drops suspended from a cable, attached to pilings, attached to buoys at the water surface, or suspended mid-depth in the water column. Electrodes can also be flush-mounted on the river bottom in concrete so that the structure does not alter water flow, catch debris, or impede boat passage (Figure 2). The amount of power required for barrier operation increases with increasing water conductivity. In brackish water, power requirements become significantly large. Power requirements for the barrier also depend on the type of current selected. Constant DC barriers require more power than pulsed DC.

Figure 2. Example of an electric barrier with bottom flush-mounted electrodes at Quinault Fish Hatchery, Washington.

Smith-Root, Inc. (Vancouver, Washington) has found that the most effective electric barrier contains electric field lines going from head-to-tail along the fish so that the fish receives maximum current across the length of their body. Fish typically swim aligned with the flow; therefore, the electrical field is most effective with field lines running parallel to the water flow. When fish turn sideways, the electric pulse is minimized. In this orientation, fish are swept downstream of the barrier. Smith-Root has developed a graduated field fish barrier (Figure 3, Smith-Root, Inc. 2012). To redirect upstream migrating fish, the voltage gradient progressively increases as the fish moves upstream through the barrier. This design allows fish to turn away from the field while experiencing minimal discomfort. Pulse generating units that control the electrical field are adjusted individually to provide a desired increasing voltage gradient between successive electrodes. The voltage level should be low enough on the downstream end to cause the target fish species to avoid the electric barrier. On the upstream end, the barrier should be set high enough to cause significant discomfort or to induce narcosis (temporary paralysis) depending on project requirements for exclusion.

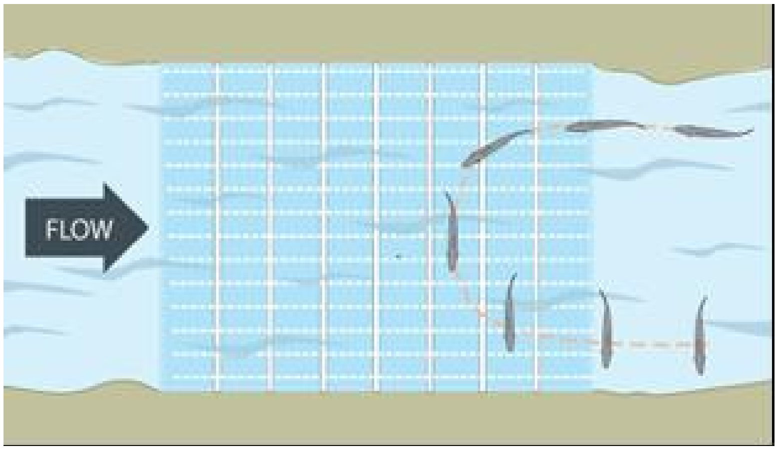

Figure 3. Schematic of fish approaching a graduated field fish barrier (Smith-Root, Inc. 2012). Fish swimming with their head into the flow will turn sideways to minimize the electric pulse. In this orientation, fish are swept downstream of the electric field by water flow.

Safety of Electric Barriers

Electric barriers pose certain safety risks to commercial vessels, recreational boats, and people in the water in the vicinity of the barrier. Power settings on electric barriers are designed to be non-lethal to humans and fish. When low frequency pulsed DC is used, pulse frequency and duration can be set well below the human electrocution threshold of a typical ground fault interrupter (Figure 4). Therefore, people who inadvertently come in contact with the barrier should not be harmed. There have been no reports of serious injury or human mortality due to an electric barrier (Burger *et al*. 2012); however, there have been reports of animals killed by electric barriers (Bark *et al.* 2011). Two humans floated through an electric barrier in Michigan when their canoe capsized, but there were no injuries (Burger *et al.* 2012). The barrier owner should work with nearby landowners to diagnose and mitigate safety risks. Near the Chicago Sanitary and Ship Canal electric barriers, no unsafe electrical potential or corrosion have been reported on nearby fences, pipelines, or bridges, although a local traffic light has malfunctioned when multiple barriers operate at once (USACE 2013).

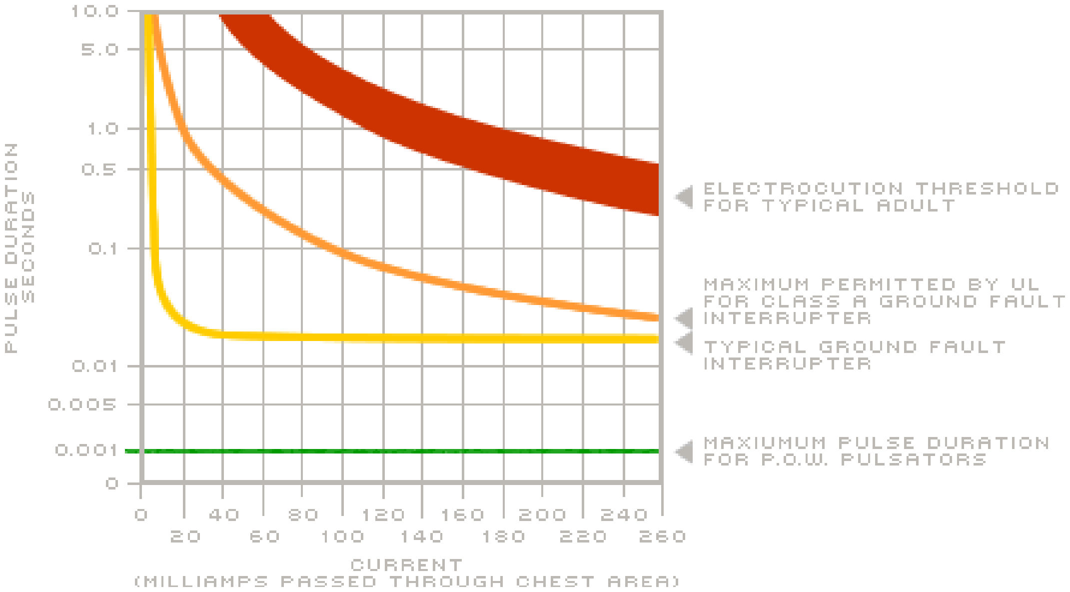

Figure 4. Comparison of current produced by a Smith-Root pulsator unit versus the electrocution threshold for a typical adult (Smith-Root, Inc. 2012).

Vessels of all types can safely pass through barriers without harm to occupants when safety requirements for each specific site are followed. For example, the U.S. Coast Guard has designated the heavily-trafficked Chicago Sanitary and Ship Canal electric barrier reach a “restricted navigation area” where barges must be tied together with steel cables to ground the entire unit, no passing is permitted, and all passengers must wear Type I life vests (USACE 2013). In other locations, boat traffic may be restricted if an alternate route is readily available.

Access to the barrier should be limited. Warning signs, lights, fencing, and/or motion detectors can be installed as safety features. Soft-start pulsing to disperse fish near electrodes upon start-up may be incorporated into a project if desired (Ostrand *et al.* 2009).

Physical and Electrical Characteristics of an Effective Electric Barrier

Electric barriers range in width from a few meters, at structures such as irrigation diversions (Sechrist *et al.* 2009), to as wide as 57 m, such as the one in the Chicago Sanitary and Ship Canal (Moy *et al.* 2011). Likewise, water depth at these barriers can vary from less than 1-m deep (Savino *et al.* 2001; Clarkson 2004) up to 7.7 m (Moy *et al.* 2011). Some barriers employ a combination of electrodes suspended in the water column and cable running along the bottom, while others are completely submerged in a plate design, allowing boat traffic and debris to float freely across the barrier (Burrows 1957; Palmisano and Burger 1988; Moy *et al.* 2011). While electrodes can be secured to the channel bottom via means such as sandbags (Palmisano and Burger 1988), canvas sheets (Savino *et al.* 2001), or wooden platforms secured to the substrate (Swink 1999), more permanent structures such as concrete weirs or aprons, or some other solid substrate on the channel bottom can be used (Clarkson 2004; Bark *et al.* 2011; Moy *et al.* 2011). These artificially created platforms (or the manmade canal itself) allow for a uniform depth across the channel bottom providing for an even distribution of electrodes. Furthermore, a substrate parallel with the water surface promotes uniform flow across an electric barrier (Burrows 1957; Palmisano and Burger 1988; Moy *et al.* 2011).

Fish mortality can occur when fish are stunned by electrical current but do not float out of the electrical field because of eddies or slow flowing areas (Burrows 1957; Palmisano and Burger 1988). A suitable location should be chosen where installation of the barrier allows for this, or the waterway needs to be modified to accommodate this scenario (Burrows 1957; Clarkson 2004). Clarkson (2004) notes that weir structures that support an electrical array may increase water velocity over the barrier, thereby making it more difficult for fish to pass. In the event an upstream moving fish is stunned by the barrier, water velocities must also be sufficient to prevent the momentum of the fish from allowing it to pass upstream of the barrier and potentially recover (Burrows 1957).

Water level fluctuations can cause issues during barrier operation. If the water level drops sufficiently, fixed electrodes may become exposed. During low flow events associated with the Central Arizona Project, some grass carp (*Ctenopharyngodon idella*) were able to pass the barrier (Clarkson 2004). It was suspected that these large-bodied fish were not exposed to enough of the electrical gradient when the water depth was only 5–8 cm deep. A suggested addition was the installation of vertical obstacles that would prevent fish passage when water depths were this low. Conversely, rising water levels have the potential to rise above fixed cable/hanging electrodes, providing an area above the array where the electrical field may be insufficient to deter fish.

Other factors that need to be considered prior to installation of an electric barrier include proximity to a power source, operational protocols that include system checks and monitoring, and boat/recreation traffic in the area. Sparks *et al.* (2010) note that metal hulled boats can negatively affect barrier operation. It was suspected that the one incidence of a common carp (*Cyprinus carpio*) successfully crossing the barrier in the Chicago Sanitary and Ship canal may have occurred when the fish traveled near the hull of a metal-hulled tow, which could have distorted the electrical gradient. Lightning strikes and mechanical breakdown of equipment can be a cause of frequent barrier failure (Clarkson 2004). Even though lightning-arresting measures were eventually installed on Central Arizona Project barriers to prevent damage from these events, damage to system components still occasionally occurred (Clarkson 2004). Backup generators may be employed to reduce the likelihood of barrier failure in the loss of the primary power source.

Use of Electric Barriers for Returning Adult Salmonids

Several salmon hatcheries, particularly in the Pacific Northwest, use electric barriers to divert fish towards the hatchery (Tschaekofske *et al.* 2004; USFWS 2009). For instance, the Quilcene National Fish Hatchery (NFH) uses an electric weir to divert coho salmon (*Oncorhynchus kisutch*) from the Big Quilcene River, the Makah NFH diverts Chinook and coho salmon and steelhead from the Sooes River, and the Quinault NFH diverts Chinook, coho, and chum salmon (*Oncorhynchus keta*) and steelhead from Cook Creek. While electric barriers are often used at salmon hatcheries to divert returning adults, published information regarding their efficacy is rather limited (Tschaekofske *et al.* 2004; Burger *et al.* 2012). More readily available research often pertains to the use of electric barriers to restrict further distribution of nuisance or invasive species.

Electric barriers have the potential to greatly reduce upstream migration into undesired areas. Of 2,094 sea lamprey (*Petromyzon marinus*) released in Jordan River, Michigan, only 0–1.8% (95% confidence interval) were estimated to have passed an upstream electric barrier (Swink 1999). Only one of 130 common carp released below the electric barrier in the Chicago Sanitary and Ship Canal made it upstream of the electric barrier (Sparks *et al.* 2010). After a physical barrier was retrofit with an electric barrier, only one grass carp escaped an embayment of Lake Seminole, Georgia (Maceina *et al.* 1999). No salmon were recorded passing upstream of a hanging-electrode AC array on the Entiat River, Washington (Burrows 1957). Barring power outages or low-flow conditions, electric barriers in the Central Arizona Project successfully prevented grass carp from migrating upstream in canals (Clarkson 2004).

Swink (1999) and Sparks *et al.* (2010) observed fish stacking up below barriers, indicating an "urge to migrate," even though fish were unable to pass the barrier. Where electric barriers have been used to prevent upstream movement, an alternative route is often used to divert target fish into a facility, such as a hatchery (Tschaekofske *et al.* 2004; USFWS 2009), or into an area where trapping can occur (*e.g.*, sea lamprey blocked from Jordan River and diverted into downstream Deer Creek; Swink 1999). Even though fish may be successfully deterred from areas upstream of an electric barrier, it should be evaluated whether or not the fish will navigate towards the preferred area following their encounter with the barrier. Furthermore, Sparks *et al.* (2010) note that jumping fish could conceivably jump across an electric barrier in response to encountering the electric field. Because salmon are strong swimmers and jumpers, the upstream to downstream electrical gradient needs to be large enough to prevent this scenario (Burrows 1957; Stuart 1962).

Effects of Electricity on Health of Salmon and Other Fish

Sublethal effects from electroshocking are not always visible (Nielsen 1998). Likewise, electroshocked fish with no external signs of injury often exhibited internal injuries in populations of fish exposed to repeated electroshocking events (Kocovsky *et al.* 1997). A balance between the ideal response of the target species/fish size (*i.e.*, deterrence without injury/long-term detrimental effects) and the electrical parameters necessary to elicit such a response needs to be considered. Often, electrical settings to maximize deterrence or diversion and those to minimize injury to fish are inversely related.

It is generally accepted that DC current is less harmful to fish than AC current (EPA 2000); therefore, much of the following discussion focuses on DC only. While AC may be more effective at preventing fish passage, survival is generally greater when DC is used (McLain 1957; Palmisano and Burger 1988). An efficient barrier, when deterrence is the objective, should block the target species with minimal or no adverse effects (McLain 1957). While long-term survival of spawning Chinook salmon is not a paramount concern since they die shortly after spawning, short-term fitness is essential for fish to successfully reach suitable spawning grounds. An efficient barrier should not adversely affect fish fecundity following electrical exposure.

As DC pulse width ("on" time of electric pulse) and voltage increased, downstream-moving round goby (*Neogobius melanostomus*) were deterred at a greater rate (Savino *et al.* 2001). Similarly, as pulse width increased from 1 ms to 2 ms, Swink (1999), noted a reduction in lamprey crossing an electric barrier on the Jordan River, Michigan. In this instance, other fish species (longnose sucker, *Catostomus catostomus*, and rainbow trout, *Oncorhynchus mykiss*) were also exposed to the electrical gradient at the barrier for 5 s and monitored 7-d post-exposure. No visible injuries occurred to these fish, nor did any mortality result during the 7-d observation period. In general, increasing pulse width and voltage and using AC instead of DC results in more deleterious effects to fish.

Rainbow trout exposed to either pulsed (300 V, 4 ms pulse width, 30 Hz) or continuous DC (single and multiple times) were monitored for 147 d post-shocking (Ainslie *et al.* 1998). Fish were x-rayed at the end of the study to check for damaged vertebrae. Mortality was negligible across treatments, though a greater incidence of injury was reported for fish exposed to pulsed DC. However, the number of vertebral injuries was greater for DC compared to pulsed-DC treatments. Nonetheless, growth rates were not significantly different among treatments. Rates of injury were also generally related to fork length of the fish (*i.e.*, the longer the fish, the greater the occurrence of injury). A similar observation of increasing rates of injury with increasing pulse rates to rainbow trout was also reported by Sharber *et al.* (1994).

In another laboratory study, rainbow trout were exposed to 30 s of pulsed DC (5–8 pulses/s, 40–60 ms pulse width, 0.75–1.00 V/cm; Maxfield *et al.* 1971). Fish were allowed to mature until spawning and the offspring of this generation were observed up to the feeding stage. In this instance, electroshocking did not affect survival or growth of the test fish to spawning. Fecundity was also not adversely affected. Average survival of fry to feeding stage was similar between controls and treatment groups.

Survival of eggs from electroshocked female Chinook salmon was consistently lower, though not statistically so, than controls (pulsed DC, 30 Hz, 275-350 V; Barnes *et al.* 1999). However, this could have been an artifact of handling stress. The duration of electrical exposure was not mentioned, though the authors relate their findings to electrofishing and fish handling in the field, not necessarily exposure to an electric barrier. Likewise, pink salmon (*Oncorhynchus gorbuscha*) eggs and milt exhibited reduced viability after electrical exposure (Marriott 1973); however, this was after exposure to 110-V AC.

Effects of Electrical Exposure on Delta Smelt and Sturgeon

Relatively few studies are available regarding the effects of electrical exposure to sturgeon. Age-1 and -2 juvenile white sturgeon (*Acipenser transmontanus;* mean fork length 277 and 439 mm, respectively) exposed to either pulsed or continuous DC (150 V for 3s; pulsed DC at 60 Hz, 6 ms pulse width, and 36% duty cycle) were observed for recovery time and injury (Holliman and Reynolds 2002). No notochord injuries were present post-exposure, though some hemorrhaging injuries were recorded. A greater incidence of injury occurred with pulsed-DC compared to DC exposure. Larger white sturgeon (mean fork length = 39.9 ± 2.5 cm) were exposed to a barrier designed to deter sea lions (*Zalophus californianus*; Ostrand *et al.* 2009). One mortality was reported following a continuous exposure to the barrier (530 V, 2 pulses/s, 0.4 ms pulse width). After a 3-min exposure to the electric current, 4 of 5 euthanized sturgeon showed no apparent notochord injuries or hemorrhaging, but one fish had a hemorrhage in its dorsal musculature. The authors note that sturgeon, in the vicinity of an electric barrier, are likely to alter their behavior to avoid the area.

No information is readily available regarding effects of electric barriers on delta smelt. However, the electrical settings necessary to elicit the desired response in fish such as salmon, are often insufficient to cause negative consequences in smaller fish, such as delta smelt (Newman and Groves 1960; Dolan and Miranda 2003). Clarkson (2004) noted that red shiners released in the electrical field of a barrier designed for carp did not tetanize even though the voltage gradient of the electrical field (1.3–1.6 V/cm) was within the threshold range for freshwater fish (0.05–5.5 V/cm). This suggests that barriers designed to divert larger fish, such as carp or salmon, operated within a range to prevent injuries to these fish, would likely not cause adverse effects to smaller fish, such as delta smelt.

Electrical exposure to the eggs of these fish could reduce viability. However, sturgeon broadcast spawn and eggs are likely to settle into crevices between substrate (Beamesderfer *et al.* 2007); delta smelt eggs are demersal and likely to adhere to the substrate in the area of spawning (Moyle *et al.* 1992). Unless green sturgeon or delta smelt are spawning in the vicinity of the electrical barrier, it is unlikely that their eggs would encounter the electrical gradient. After hatching, though, it is possible that drifting larvae could encounter the electric current produced by the barrier. While smaller fish are frequently unaffected by the electric currents needed to elicit responses from larger fish, larval fish may be more sensitive to electrical exposure.

Application to Delta Cross Channel Electric Barrier

Based on literature, use of an electric barrier to divert upstream migrating adult Chinook salmon away from the Delta Cross Channel may be effective and the concept should be further investigated. Studies show that electric barriers are more successful at deterring upstream migrating fish than downstream migrating fish, especially when there is an attraction flow to guide fish past the barrier. The proposed electrical barrier should use direct DC or pulsed DC, since DC is less harmful to fish than AC. A graduated field fish barrier is recommended. The voltage level should be low enough on the downstream end to allow adult salmon to avoid the electric barrier. The voltage gradient should progressively increase as fish move upstream through the barrier until they experience significant discomfort. Since fish of concern may come in contact with the barrier from the upstream side, it may be appropriate to graduate the voltage gradient on the upstream end to protect those fish.

For this project, a bottom flush-mounted system is preferred as it will not alter water flow, catch debris, or impede boat passage. Installation of an artificial channel section containing bottom-mounted electrodes will allow for more uniform depths and flows at the barrier location. Tidal influences may create significant changes in water quality near the Delta Cross Channel. Water quality at the proposed installation site should be determined, since water conductivity affects electrical settings and power requirements. Backup generators will be needed to reduce the likelihood of barrier failure in the loss of the primary power source.

Design of an electric barrier should be viable for the channel widths and depths expected at the proposed installation locations. Water depths should be large enough to produce a consistent electrical field, but not so large that the electrical field does not penetrate through the entire water column if a bottom-mounted system is used. The barrier should be long enough to prevent salmon from jumping across the barrier in response to encountering the electric field. Water velocities should be high enough to push stunned fish off of the electric barrier where they can recover. Eddies and stagnant zones should be avoided as they can increase the risk of mortality. Because the channel is bifurcated downstream of the Delta Cross Channel, it is important to determine which route upstream migrating salmon are more likely to encounter in order to choose the best location for a permanent electrical barrier. Since the highest attraction flow will occur through the electric barrier when the Delta Cross Channel gates are open, return paths to the preferred migration route should be evaluated to ensure that upstream migrating salmon will return to the Mokelumne River after being diverted.

Safety at the proposed barrier site is paramount. Although electric barriers are designed to be non-lethal to humans and fish by using low frequency pulsed DC, warning signs, lights, and fencing should be included at the site and additional features such as motion detectors and soft-start power ramp-up to disperse fish near electrodes should be considered. Safe passage of vessels through the electric barrier has been proven at other electric barrier locations; however, boat access could be restricted if alternate routes are readily available. Studies show that increasing electrical parameters such as pulse width, voltage, and frequency causes a greater number of deleterious effects to fish. If electrical parameters are set with the goal of causing an avoidance response rather than tetanus, injury to fish is typically low or nonexistent. Based on the literature review, the fecundity of electroshocked salmon and subsequent survival of fry should not be adversely affected if low frequency pulsed DC is used.

The literature search did not uncover any studies with the same application as the project at the Delta Cross Channel. Several fish hatcheries in the Pacific

Northwest use some type of electric barrier to divert adult salmon towards the hatchery. Although electric barriers are likely successful at obtaining return numbers to the hatcheries, published information regarding their efficacy as an exclusion barrier is limited. In various situations, DC barriers have been shown to reduce upstream migration of sea lamprey, common carp, and grass carp and a hanging-electrode AC array has been shown to reduce upstream migration of salmon. Although no studies were found where a DC electric barrier was used as an exclusion barrier for upstream migrating adult salmon, this literature review indicates that an electric barrier could be successful at achieving project goals.

Few studies are available regarding the effects of electrical exposure to sturgeon. Some injuries were recorded, but voltage and frequency levels were higher in literature than what would be used in a graduated field fish barrier. Soft-start pulsing to disperse fish near electrodes should be considered if sturgeon are expected near the proposed barrier location. No information is readily available regarding effects of electric barriers on delta smelt. However, the electrical settings necessary to divert larger fish such as salmon and carp without injury should not cause adverse effects to smaller fish such as delta smelt. Electrical exposure to the eggs of sturgeon and delta smelt could reduce viability; however, unless sturgeon or delta smelt are spawning in the vicinity of the electrical barrier, it is unlikely that their eggs would be affected. Central Valley steelhead may also encounter the barrier. Adults may be present July–May and juveniles can remain in the river for up to two years before emigration (McEwan 2001). Because of the similarities between steelhead and Chinook salmon, response of juvenile and adult steelhead to an electrical barrier would likely be similar to Chinook salmon.

Regulatory agencies should be contacted to determine if federally listed fish and their eggs/larvae will be present in the proposed location of the electric barrier during the operation period. If fishery experts determine that these species may be adversely affected by barrier operation, mitigation techniques may be used or additional studies may be requested.

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Appendix A

Table 1. Key points regarding electrical barriers, health effects, and threatened and endangered species from reviewed literature.

No.	Title	Reference	Selective Description Based on Literature Review Topic
Electric Barriers for Adult Salmonids			
1	Evaluation of Quinault National Fish Hatchery adult salmonid electric barrier.	Bark, R.C., M.D. Bowen, and C.D. Svoboda. 2011.	Several safety measures need to be addressed to operate the electric barrier safely for humans, mammals, and migrating fish. A dead black bear (*Ursus americanus*) was found next to the electric barrier in October 2005. It is thought that the bear was attempting to access fish near the barrier. To keep humans and animals away from the electric barrier, there is an 8 ft high chain link fence with three strands of looping barbed-wire. However, each end of the fence stops just beyond the barrier on the upstream and downstream bank of Cook Creek and is passable by walking onto the creek bank around the fence. The gravel-cobble substrate deposits immediately downstream of the barrier where the creek widens and water velocities decline, thereby creating access to the electric barrier. Several signs are posted on the fence and above the downstream end of the barrier hanging on a cable to warn people of the electrical hazard created by the barrier. Authors recommend safety improvements: further inhibiting access to the concrete slab with fencing and vertical retaining walls, hiring a security guard and imposing fines, and constructing nearby fishing access to encourage fishing in a safe area. Modifications to the electric barrier could include: adjusting the voltage gradient, installing ground fault interrupters, and installing laser-motion detectors. Modifications to the channel could include: installing a wing wall to better flush substrate downstream, removing downstream debris and gravel, and narrowing the channel width at the barrier.
2	Effectiveness of an electrical barrier in blocking fish movements.	Barwick, D.H. and L.E. Miller. 1990.	Operation of a graduated field fish barrier blocked gizzard shad (*Dorosoma cepedianum*), rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), golden shiners (*Notemigonus crysoleucas*), and largemouth bass (*Micropterus salmoides*) during simulated modes of hydropower generation in an 80-ft-long x 6-ft-wide canal. Total exclusion rates were 95-97% for nongeneration, 94-97% for generation, and 83-84% for pumping. Exclusion results were not specified by species. The pulsator units were set to 10 pulses/s and 200-300V for a measured range of 0.5 V/cm to 1.7 V/cm with a handheld probe and oscilloscope.
3	Diversion of adult salmon by an electrical field.	Burrows, R.E. 1957.	An electrical barrier is described as used in the Entiat River in 1953. It consisted of a series of conduit suspended across the river with a submerged ground line. 110-V alternating current was used. Electrical barriers were suggested for use over mechanical barriers because the latter often become ineffective at higher velocities and also impede stream flow. While documented that

No.	Title	Reference	Selective Description Based on Literature Review Topic
			this setup has the potential to kill adult salmon, limitations for deployment were described. These include a minimum velocity (in this case, 3 ft/s) to sweep stunned salmon out of the electrical field, as well as laminar flow (eddies can cause fish to remain in the electrical field resulting in injury or death). The arrangement provided was successful for deterring salmon in water up to 8-ft deep and 200-ft across. No adverse effects to fingerling salmon were noted and they passed freely up- and downstream of the electrical barrier, though they were stunned if they swam within 3-4 inches of the hanging electrodes. However, recovery was rapid after floating downstream of the electrical field.
4	Operation of a temporary electrical fish barrier, San Joaquin River above the confluence with the Merced River, fall 1992.	California Department of Fish and Game. 1993.	In fall 1992, a temporary Smith-Root graduated electric barrier (0.5-2.5 V/in, water conductivity 2,300-3,500 µS) was installed on the mainstem San Joaquin River immediately upstream from the confluence with the Merced River. The barrier was installed to prevent fall-run Chinook salmon (*Oncorhynchus tshawytscha*) from straying into westside agricultural drains and canals. An array of electrodes was embedded in a canvas sheet at the river bed (30 ft upstream-to-downstream and 125 ft wide). In the 3 years before installation, approximately 60-79% salmon continued up the San Joaquin River. In the first year of installation, approximately 1% continued up the San Joaquin River (11 of 988 salmon). During this year, flows in the San Joaquin River were low and flows in the Merced River were high which may have been a factor in the high success rate.
5	A review of fish capture methods for salmon research.	Carter, T.J., I.P. Smith, and A.D.F. Johnstone. 1997.	This report contains a small section on fish capture methods using electric fields. A Smith-Root electric barrier was installed on the Michigan River and was found to be effective at stopping upstream migrating sea lamprey (*Petromyzon marinus*) and steelhead (*Oncorhynchus mykiss*; Dawson and Smith 1995). A repelling electric screen was installed in France which successfully excluded upstream migrating Atlantic salmon (*Salmo salar*) from a hydroelectric plant (Gosset *et al*. 1992) with no apparent effect upon subsequent movements of the fish.
6	Effectiveness of electrical fish barriers associated with the Central Arizona Project, 1988-2000.	Clarkson, R.W. 2004.	This report describes the operation of a number of waterways in the Central Arizona Project that divert Colorado River water into the Gila Basin. To prevent the spread of invasive fishes, electrical barriers were installed at several locations to prevent upstream movement into further water bodies. Most sites were between 15.8 and 18.5 m wide and had a maximum depth of 2.5 m. Barriers were designed by Smith Root, Inc. The barriers were designed to maintain a minimum electrical gradient of 1 V/cm at the water surface, with a 25 ms pulse width and 2 pulses/s. Canals were concrete lined and concrete weirs were installed on the bottom of these canals to provide a foundation for mounting the electrodes, create uniform depth, and increase the water velocity over the barrier, adding another variable to prevent upstream fish passage over

No.	Title	Reference	Selective Description Based on Literature Review Topic
			the barrier. During the operation period mentioned, several power outages occurred, typically from personnel or mechanical failures. Lightning strikes were noted on more than one occasion to cause outages as well. In some instances, it was noted that grass carp (*Ctenopharyngodon idella*) were able to navigate one of the electric barriers, either during an outage or during low flows that created low water depths over the barrier (5-8 cm). In another instance, red shiners were released in the electrical field of a barrier and observed. While the fish swam erratically, none were tetanized, and some successfully navigated upstream of the barrier. While the voltage gradient at the electrodes (1.3-1.6 V/cm) was within the threshold to tetanize freshwater fish (0.05-5.5 V/cm), it did not happen in this case. However, because the fish were released within the field, it is unknown how they would behave having approached the electrical field from downstream. Vertical additions to the concrete weir could prevent upstream movement of large-bodied fish, such as grass carp, in future instances of low water levels when these fish may not be completely submerged. In addition, the author notes that remote monitoring data are a prerequisite to document and identify barrier failures.
7	Effectiveness of three barrier types for confining grass carp in embayments of Lake Seminole, Georgia.	Maceina, M.J., J.W. Slipke, and J.M. Grizzle. 1999.	In an attempt to evaluate the ability to confine grass carp (*Ctenopharyngodon idella*) within defined areas of a water body, three barriers were evaluated: two physical barriers (one allowing boat passage) and a physical v-shaped barrier with an electrical barrier installed. Fish were affixed with radio tags and tracked to determine retention within the boundaries of the barrier. Problems arose from either fish dying or tags being expelled. However, escapes from the combined physical/electric barrier were much less (1.3%) than either of the other two barriers (9 and 23%). The electric barrier was installed by Smith-Root with the following operational parameters: 3-4 V, 12-A peak current, 10-ms pulse rate, 500-ms duty cycle.
8	The control of the upstream movement of fish with pulsated direct current.	McLain, A.L. 1957.	Two electrical barriers were used in Michigan: one on the Chocolay River and one on the Silver River. Each array consisted of a downstream DC array designed to divert fish into a trap and an upstream AC array designed to prevent any upstream movement of fish that were able to navigate upstream of the DC array. Typical DC array settings were 110 V, 66% duty cycle, and 3 pulses per second. The Chocolay River was approximately 50 ft wide and 2-6 ft deep with water conductivity of 63.78-136.50 µS/cm and a velocity of 1.5-2.5 ft/s. The Silver River was approximately 70 ft wide and 3 ft deep during low water conditions with a velocity of 0.5-2.0 ft/s and water conductivity of 30.70-104.82 µS/cm. During operation from April 13-July 25, 1956, discounting downstream mortality, mortality of upstream moving fish on the Chocolay River was 1.9%. Similarly for the Silver River, mortality from April 20-June 30, 1956, discounting mortality of downstream moving fish, was 1.3%. Issues during operation included mechanical failure of the device providing pulsed DC, fluctuating water levels which changd the electrical fields, and the diversion trap filling to capacity during periods of high fish migration.

No.	Title	Reference	Selective Description Based on Literature Review Topic
9	The Chicago Sanitary and Ship Canal aquatic nuisance species dispersal barrier.	Moy, P.B., I. Polls, and J.M. Dettmers. 2011.	A micropulsed direct current array was installed in the Chicago Sanitary and Ship Canal to limit invasive species dispersal between the Chicago River and Lake Michigan. The barrier was installed in a canal approximately 57-m wide and 7.7-m deep with a velocity of 0.15-1.5 m/s. Limestone walls of the canal were perpendicular to the bottom, providing uniform symmetry across the canal. The electrical field was weaker in the margins extending away from the barrier and greater towards the center in an attempt to deter fish before reaching the barrier's maximum strength where fish would likely be stunned. Concerns of operation were corrosion of electrode cables and power outages from lightning strikes.
10	Relationship of fish size and water velocity to the fish guiding effectiveness of a single-row electrode array.	Newman, H.W. and A.B. Groves. 1960.	This particular study pertained to guiding fingerling silver coho salmon (*Oncorhynchus kisutch*) using an electrode array placed 40 degrees to the water flow. In this instance, the fish were moving in a downstream manner. Results demonstrated an inverse relationship to the ability to guide fish and fish size. Conversely, water velocity negatively affected the ability of arrays to "guide" small fish, likely because they lacked the swimming ability to navigate the array with increasing flows.
11	Use of a portable electric barrier to estimate Chinook salmon escapement in a turbid Alaskan river.	Palmisano, A.N. and C.V. Burger. 1988.	An electric barrier was used on a braided channel of the Killey River to divert fish into the opposite side of the river in order to collect adult Chinook salmon (*Oncorhynchus tshawytscha*) in a weir for the purpose of a mark-recapture study. Particulars of the electric barrier were width = 27 m, depth = 1-2 m, velocity = 0.6-1.5 m/s. Alternating current was originally used but changed to direct current. This was marked by a significant decrease in mortality of the ratio of captured/killed fish (0.29 to 0.03). Other factors found to influence mortality included: slow/no velocity areas where stunned fish were not flushed out of the electrical field which caused increased mortality; reduction of the contact of electrical cables with fish by securing the array to the riverbed using sandbags; re-orienting the anode perpendicular to the cathode to further reduce the chance of direct contact to fish. Optimal settings of the array were direct current at 168 V, 37-ms pulse width, 120 pulses/s, and 1 A current.
12	Use of electrical barriers to deter movement of round goby.	Savino, J.F., D.J. Jude, and M.J. Kostich. 2001.	The primary purpose of this study was to investigate the use of electric barriers to prevent downstream movement of round gobies (*Neogobius melanostomus*) and further application in preventing their spread into the Illinois Waterway System and Mississippi River drainage. While not directly applicable to the topic of interest here (*i.e.*, upstream salmon guidance), some of the primary results may be. Factors that significantly affected deterrence from barrier crossing were an increasing pulse duration (0.05 vs. 5 ms) and increasing voltage (70V vs. 100V). Increasing voltage resulted in an increased voltage gradient at the barrier (70V, 2.6

No.	Title	Reference	Selective Description Based on Literature Review Topic
			V/cm and 100V, 4.9 V/cm).
13	Quinault National Fish Hatchery Electric Barrier	Smith-Root website.	The graduated electric weir contains a main deck and a smaller low flow section. There are seven steel rail electrodes embedded into the Insulcrete™ decks and side walls. The barrier works well to divert salmon and steelhead. There has been considerable maintenance associated with material bedload. It has also been found that the orientation of the original weir and the barrier is not consistent with the now existing stream flow, resulting in uneven water depth at low flows.
14	Evaluation of an electric fish dispersal barrier in the Chicago Sanitary and Ship Canal.	Sparks, R.E., R.L. Barkley, S.M. Creque, J.M. Dettmers, and K.M. Stainbrook. 2010.	An electric barrier was installed in the Chicago Sanitary and Ship Canal. While originally designed to prevent downstream movement of round goby (*Neogobius melanostomus*), installation of this barrier occurred after these fish had already dispersed downstream. Instead, the efficacy of this barrier was evaluated to determine the potential to reduce upstream movement into Lake Michigan by other species, such as grass carp (*Ctenopharyngodon idella*). In this instance, common carp (*Cyprinus carpio*) were used as a surrogate. Carp were acoustically tagged (n=130) and monitored for movement within the canal. Of 130 fish tagged, one fish successfully navigated upstream of the barrier, which also coincided with an upstream-moving barge. The barge was thought to have disrupted the electrical field allowing the fish to pass upstream. Aspects of the barrier are further described in Moy *et al.* 2011.
15	Effectiveness of an electrical barrier in blocking a sea lamprey spawning migration on the Jordan River, Michigan.	Swink, W.D. 1999.	A pulsed DC barrier was installed on the Jordan River, Michigan to prevent escapement of upstream migrating sea lamprey (*Petromyzon marinus*). Electrodes were attached 1 m apart on a wooden platform flush-mounted on the riverbed. Originally, electrical settings were 1-ms pulse width and 10 pulses/s but later increased to 2-ms pulse width and 10 pulses/s. Additionally, several species of fish were held over the barrier in non-conductive baskets for up to 5 s to test for visible injury and mortality over a 7-d monitoring period. Paired releases of adult lamprey, tagged with Dennison tags and a redundant coded wire tag (in case of loss of Dennison tag), were released up- and downstream of the barrier. Fyke nets were placed upstream of the barrier in an attempt to capture released fish. However, the nets only covered ~50% of the river. Capture efficiency, determined by the upstream released lamprey, was 15-26%. Of 2,094 lamprey released below the barrier, only 1 was recovered upstream. This accounted for 0-1.8% of downstream lamprey successfully passing the barrier after adjusting for fyke net efficiency. However, at the high settings (2 m/s pulse width, 10 pulses/s) no lamprey were recovered. 95% confidence interval estimates 0-1% of lamprey passing at these settings. Of the fish held over the barrier to monitor for injury and survival, no visible injuries were apparent and no fish died over the 7-d monitoring period.

No.	Title	Reference	Selective Description Based on Literature Review Topic
16	An assessment of potential anadromous fish habitat use and fish passage above Quinault National Fish Hatchery in Cook Creek.	Zajac, D. 2004.	This report presents options and recommendations regarding anadromous fish use of the habitat above Quinault National Fish Hatchery (NFH) in Cook Creek. The 2002 electric barrier design consists of electrodes embedded in a concrete deck that emit a graduated electrical field diverting fish into the hatchery ladder. The weir also contains a low flow bypass section that can be operated separately from the main weir. The weir is not a physical block to fish movement if it is not electrified. Usually, the weir is activated year round. Active passage of adult salmonids into habitat above the hatchery has never occurred. However, some fish (cutthroat, steelhead, coho and chum salmon; *Oncorhynchus clarki*, *O. mykiss*, *O. kisutch*, and *O. keta*, respectively) are known to move upstream during power outages and high flow events (Tom Kane, FWS, per. comm., 1999).
Effects of Electric Barriers on Salmonid Health, Stamina, or Reproductive Capability			
1	Effects of pulsed and continuous DC electrofishing on juvenile rainbow trout.	Ainslie, B.J., J.R. Post, and A.J. Paul. 1998.	Three-hundred fifty rainbow trout (*Oncorhynchus mykiss*) were subjected to various treatments of electroshocking to determine rates of injury and effect on growth, both at the individual level and modeled at the population level. These treatments included direct current (DC) and pulsed direct current (PDC) and combinations of these with single-pass and three-pass electroshocking. The electrofisher was set at 300 V for both DC and PDC treatments. For PDC treatments, a 30 Hz cycle and 4 ms pulse width were used. Water conductivity was 285 µS/cm and temperature was 10.5°C. Fish were monitored 147 d post-treatment. Mortality was negligible between control fish and electroshocked fish (<1%). Fish exposed to PDC had a higher rate of injury than those exposed to DC only and fish exposed to multiple electroshocking passes had greater rates of injury than with the single pass. Injury rates of fish exposed to DC only was not significantly different than the control group. However, of the fish with injuries from DC exposure, a greater number of vertebrae were damaged than those exposed to PDC. Growth rates were different between treatments, but only marginally so.
2	Technical notes: practical observations on the use of eggs from electroshocked females during spawning of inland fall Chinook salmon.	Barnes, M.E., J.P. Lott, W.A. Sayler, and R.J. Cordes. 1999.	Eggs were collected from ripe female Chinook salmon (*Oncorhynchus tshawytscha*) at Whitlocks Spawning Station, South Dakota. Eggs were collected from both electroshocked fish as well as ones collected from a fish ladder. Fish were electroshocked with pulsed DC (30 Hz) at 275-350 V and a range of 7-14 A. Survival of eggs from electroshocked fish was consistently lower than those fish collected from the fish ladder, though not statistically significant. However, it was suggested that this difference may have been related to the additional handling stress of electroshocked fish, since they were handled more frequently, prior to egg collection than fish caught from the fish ladder.

No.	Title	Reference	Selective Description Based on Literature Review Topic
3	Effects of electroshock voltage, wave form, and pulse rate survival of cutthroat trout eggs.	Dwyer, W.P, and D.A. Erdahl. 1995.	This study focused primarily on testing the effects of various electroshocking voltages and wave forms on the survival on cutthroat trout (*Oncorhynchus clarki*) eggs. Groups of 200 eggs per replicate were shocked once during development. Each set of replicates was shocked on an even day (e.g. 2, 4, 6) through day 18. Results indicated that higher voltages had a greater effect on survival than waveform. While these results were related to reducing electroshocking-induced mortality when conducting surveys over salmon redds, the principals contained herein may relate to demersal eggs of other fish species that may pass through an electrical barrier. However, this study most likely has limited applicability to the overall health of eggs within female salmon since all the eggs in this study were electroshocked post-fertilization.
4	Spinal injury rates in three wild trout populations in Colorado after eight years of backpack electrofishing.	Kocovsky, P.M., C. Gowan, K.D. Fausch, and S.C. Riley. 1997.	Starting in 1987, fish in northern Colorado streams were electrofished using 3-pass backpack electrofishing (100 Hz, square-wave direct current, and 250-450 V; water conductivity 34-63 µS/cm). Several fish species were present including brook trout (*Salvelinus fontinalis*), rainbow trout (*Oncorhynchus mykiss*), and brown trout (*Salmo trutta*), as well as longnose sucker (*Catostomus catostomus*). Control fish were captured from sections of stream assumed to not previously been exposed to electrofishing. Fish were externally examined for previous indications of spinal injury. However, from fish sampled and x-rayed, it was found that these external examinations underestimated injury. Of 114 fish with no apparent injuries from previous electrofishing encounters, x-ray examination indicated 44% of these in fact had spinal injuries. Populations were also monitored during the study period. While none of the salmonid species displayed a decline in abundance, longnose sucker results suggested this species may have been more susceptible to deleterious effects from electrofishing.
5	Effects of electric shocking on fertility of mature pink salmon.	Marriott, R.A. 1973.	After reduced fertility was observed for salmon eggs following collection of electroshocked fish, a study was conducted to evaluate electroshocking effects on fish and eggs. Pink salmon (*Oncorhynchus gorbuscha*) were collected from the Buskin River, AK and varying combinations of shocked/non-shocked fish/eggs were combined (e.g. shocked males/non-shocked females, shocked females/non-shocked males, shocked fish/non-shocked eggs, shocked fish/shocked eggs) to determine overall survival of fertilized eggs. During the study, 110 V AC current was applied for 5 s for the shocking treatment. Results suggest that electroshocking has a more detrimental effect when ripe female fish were shocked as compared to ripe males, and that post-fertilization shocking of eggs was more detrimental than pre-fertilization shocking.
6	Survival, growth, and fecundity of hatchery-reared	Maxfield, G.H., R.H. Lander, and K.L. Liscom. 1971.	Young-of-the-year and yearling rainbow trout (*Oncorhynchus mykiss*) were shocked with pulsating direct current. Their survival, growth, and fecundity were observed to spawning size.

No.	Title	Reference	Selective Description Based on Literature Review Topic
	rainbow trout after exposure to pulsating direct current.		Their offspring were also observed until the fry reached the feeding stage for overall survival. No differences were observed across control and treatment fish as a function of the averages of these parameters.
7	Reducing electrofishing-induced injury of rainbow trout.	Sharber, N.G., S.W. Carothers, J.P. Sharber, J.C. de Vos, Jr., and D.A. House. 1994.	A number of experiments were evaluated to determine some of the characteristics of pulsed direct current responsible for spinal injury in rainbow trout (*Oncorhynchus mykiss*). Of the variables tested, pulse frequency applies most to those characteristics of interest regarding efficacy and health to fish and electric barriers. Increasing pulse frequency correlated with increasing spinal injuries in rainbow trout > 300 mm.
8	Long-term effects of electrofishing on growth and body condition of brown trout and rainbow trout.	Thompson, K.G., E.P. Bergersen, R.B. Nehring, and D.C. Bowden. 1997.	Scale annuli were used to calculate growth rates between electroshocked and non-electroshocked trout in Colorado streams. Fish were captured and tagged and re-captured the following year, and growth rate determined and compared to non-tagged fish. While several groups of fish did not meet the assumptions to accurately compare these parametrics, of the groups that met these assumptions, shocked fish were found to have a significantly reduced growth rate when compared to non-electroshocked fish.
Effects of Electricity on Delta Smelt and Sturgeon			
1	Electroshocked-induced injury in juvenile white sturgeon.	Holliman, F.M., and J.B. Reynolds. 2002.	Age 1 (mean fork length (FL) = 277 mm) and 2 (mean FL = 439 mm) white sturgeon (*Acipenser transmontanus*) were exposed to direct current (DC) and pulsed DC in an experimental tank. Fish were typically exposed to 3 s of 150 V DC. Fish were exposed to pulsed DC under similar conditions as well at a frequency of 60 Hz. Nominal voltage gradients of 1.2 V/cm were used. A greater percentage (68% vs. 10%) of hemorrhaging injuries were reported in fish exposed to pulsed DC. No significant difference in injury rates was recorded between size classes. Recovery time for fish exposed to pulsed DC was also more variable than fish exposed only to DC.
2	Behavioral and physiological response of white sturgeon to an electrical sea lion barrier system.	Ostrand, K.G., W.G. Simpson, C.D. Suski, and A.J. Bryson. 2009.	White sturgeon (*Acipenser transmontanus*) were exposed to a 2 pulse/s, 530 V electrical field designed to deter sea lions (*Zalophus californianus*). Fish typically avoided the barrier once activated. One of 15 fish died after 40 h following exposure to continuous operation of the electric barrier. Furthermore, plasma lactate was elevated in fish exposed to electroshock, compared to controls. No notochord injuries were recorded for fish euthanized for evaluation following electrical exposure.